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EXPERIMENTAL OBSERVATIONS OF AERODYNAMIC AND HEATING TESTS ON INSULATING HEAT SHIELDS

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SUMMARY

Several different types of insulating heat shields have been subjected to aerodynamic tests and radiant-heating tests in order to obtain a better insight into the problems involved when the primary structure of an aerodynamically heated vehicle is substantially cooler than the exposed external surface. One of the main problems was considered to be a proper allowance for thermal expansion caused by these large temperature differences, so that undue distortion or thermal stresses would not occur in either the outer shield or the underlying structure. A corrugated outer skin with suitably designed expansion joints was a feature of all the specimens tested.

INTRODUCTION

The high temperatures associated with the aerodynamic heating of a vehicle reentering the atmosphere have greatly compounded structural problems. One method of coping with the high-temperature environment is to provide a nonload-carrying, insulating heat shield which can tolerate the external environment and which will insulate the underlying load-carrying structure from the aerodynamic heating. With the proper amount of insulation, and in some applications, cooling, the structure can be kept within the useful temperature range for the material.

Heat-shield designs often involve a lightweight outer skin; the major design problem is one of supporting this outer skin so that it will survive in the airstream and, at the same time, will accommodate the thermal expansion due to the large temperature differences between shield and structure. This paper presents some experimental observations of aerodynamic and heating tests on a few types of heat shields supported on typical primary structures and discusses some general techniques of designing lightweight protective shields which must operate at temperatures much higher than the underlying structure.

TEST SPECIMENS

In order to allow an outer skin to be considerably hotter than an underlying structure without causing severe thermal stresses or undesirable distortion, a satisfactory means of allowing for expansion must be provided. Because a corrugated sheet can expand and contract in one direction with the application of a relatively small force, it was used as the basic component of the various designs tested. The corrugated skin also provides the necessary stiffness to transmit aerodynamic loads and resist flutter. In figure 1(a) the accordion-like movement of the corrugations is illustrated; the thermal expansion can occur with only small resultant forces at the attachment points. In the perpendicular direction, expansion must be accomplished by another means; figure 1(b) indicates the method used in the designs reported herein. The heat shield can expand away from the center support and the deflection at the end is absorbed by a flexible support which allows lateral movement but is sufficiently stiff in the vertical direction. These flexible supports divide the heat shield into several strips which should probably not exceed a width of 1 to 2 feet to prevent support deflections from becoming excessively large. The three different types of specimens which were fabricated and tested incorporated the basic expansion mechanisms shown in figure 1.

The temperature capability of the test specimens was limited by the heat-shield material used, Inconel X. However, an effort was made to employ simple design concepts which are compatible with possible fabrication techniques being developed for refractory metals, so that temperature capabilities in excess of 2,000° F would be possible. The use of rather simple corrugated shapes appeared to be a suitable method of minimizing the fabrication problem. The test specimens consisted of a thin, corrugated, outer metallic skin, usually of 0.01-inch Inconel X, a layer of insulation, and some type of representative primary structure. The heat shields were separated by the expansion joints into several individual shields which overlapped one another in a manner similar to overlapping shingles.

No attempt was made to provide completely realistic fasteners for the test specimens, nor was the insulation used one that was necessarily the best for a particular condition. In all cases, the fasteners and insulation used were adequate so that in heating or wind-tunnel tests the structural behavior was believed to be essentially that of a design using more refined insulating and fastening techniques. Details of the various designs are shown in figures 2 to 4.

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Configuration A

Configuration A, shown in figure 2, illustrates a case in which the presence of rather large deviations from a plane surface is not objectionable. Rather deep corrugations can be used and the support spacing can be large. This shield consists of a series of 12-inch-wide corrugated sheets with a corrugation depth of 1/4 inch. The supporting clips along the center line of the corrugated sheet form a truss-type connection which can resist drag forces parallel to the axes of the corrugations. The flexible supporting clips at each edge allow the corrugations to expand longitudinally from the center line and to move with respect to each other. The shield was fastened to the clips with sheet-metal screws. The height of the clips can be varied to accommodate most insulation requirements.

Configuration B

Configuration B, the second heat-shield design (fig. 3), had corrugations with a much smaller depth than that of configuration A. The edges and center of each individual shield are mounted on the stiffeners of the underlying primary structure in a manner that will allow expansion as indicated in figure 1(b). The stiffeners were designed to provide a nondeflecting support at the center line of each individual shield and to provide flexible supports along the edges. The shield was attached with screws to nuts spot-welded to the interior of the structure. There was a space of about $\frac{1}{16}$ inch to $\frac{1}{8}$ inch between the outer skin and the underlying structure so that the insulation capabilities were somewhat restricted. Insulations with very low conductivity are required for satisfactory performance for this type of attachment design.

Two types of primary structure are shown in figure 3; one consists of two corrugated sheets with corrugations oriented at right angles to each other to form a cross-ply corrugated panel (specimens 1 to 4), and the other consists of a corrugated sheet seam-welded to a flat sheet (specimens 5 and 6). The insulation placement in specimens 5 and 6 was changed from that of specimens 1 to 4 in an attempt to improve the insulation qualities of the panel.

Configuration C

The design shown in figure 4, denoted configuration C, consists of an array of two-ply corrugated outer panels approximately 12 inches square and supported by flexible clips attached to the underlying structural panel. This shield has some of the more prominent features of the first two designs. The outer corrugation, which is relatively shallow as in configuration B, is attached to a deeper corrugation which provides the strength and stiffness necessary for spanning large distances, as in configuration A. The cross-ply corrugations, which were spot-welded together, allow differential thermal expansion to take place between the two corrugated sheets when they are at different temperatures; this condition might occur during initial heating. The overall expansion of each heat-shield panel is absorbed by the flexible clips which deflect radially from the center of the panel. The height of the clips may be adjusted to accommodate the thickness of insulation required. In the design shown, the structure is water-cooled and large temperature differences between shield and structure can occur. The expansion devices must accommodate the fairly large movements associated with these large temperature differences.

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TEST CONDITIONS

Two types of environmental tests were performed. Radiant-heating tests were made on all the configurations, and wind-tunnel tests were made in the Langley 9- by 6-foot thermal structures tunnel on configurations A and B.

Radiant-Heating Tests

In the radiant-heating tests, quartz-tube lamps were utilized to bring the outer surface to a given temperature, which was maintained until the test was terminated. The distortion, if any, was observed visually during the test and the residual distortion was noted after the test. Thermocouples were placed in many locations to determine temperature distributions in the underlying primary structure as well as over the outer surface.

The maximum shield temperature corresponded approximately to the upper temperature limit for which Inconel X or other superalloys can be used as a heat shield. However, it is believed that the results of these tests will be useful in development of refractory-metal heat shields capable of sustaining higher temperatures.

Wind-Tunnel Tests

In the wind-tunnel tests the heat shields were mounted in a large panel holder at an angle of attack of 0°. Various tests involved different orientations of the corrugations with respect to the airstream. The stable tunnel conditions were a Mach number of 3, a dynamic pressure of about 3,000 pounds per square foot, and a stagnation temperature of 660° F. These conditions do not reproduce the environment for which the heat shields were designed; the temperatures are far too low, but the excessive dynamic pressure provides a rather severe test of the structural integrity of the heat shield.

TEST RESULTS

Configuration A

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<u>Heating tests</u>.- The shield design (configuration A) shown in figure 2 was mounted on a 19-inch-diameter stainless-steel cylinder for the radiant-heating tests. The cylinder was mounted in a circular radiant heater as shown in figure 5. The ends were sealed with 1-inch-thick Transite so that most of the heat which passed through the heat shield was confined and absorbed by the structure. A typical measured temperature history for the cylindrical heat shield and the underlying structure, along with a calculated temperature response of the underlying structure, is shown in figure 6. In this test, heat was applied uniformly around the circumference of the shield; the maximum temperature-rise rate was about 100° F per second. The specimen was 36 inches long and the heater was 25 inches long; therefore, there was a longitudinal temperature gradient with a rather sharp temperature drop near the ends. The temperature of the structure, as shown in figure 6, is a weighted average of many thermocouples located on the rings and skin at several circumferential stations near the midlength of the cylinder. Apparently the insulation was not uniformly placed, for deviations of as much as ±75° F from the values shown on the curve were measured along the circumference. Note the large temperature difference between outer surface and structure, especially during the early part of the test. In spite of these large temperature differences, there was no visible distortion or damage during or after the test.

The calculated temperature curve was obtained by using the following numerical procedure. The outer-surface temperature of the insulation was assumed constant with time and equal to the maximum shield temperature. The insulation was divided into five layers and the diffusion equation was written in terms of finite differences, with the assumption of one-dimensional heat flow and no heat losses from the interior surface. The heat capacity of the insulation and variation of thermal conductivity with temperature were included in the equations which were solved by the use of an electronic computer. Figure 6 shows that the measured temperature curve is lower than the calculated curve. This difference may have resulted from heat losses to the cooler ends and inaccurate values of insulation properties.

The same specimen was also heated nonuniformly around the circumference in order to determine whether the resulting thermal gradients would damage the shield. For this test, only one-third of the circular radiator was energized and the shield-temperature distribution shown in figure 7 was obtained. Note the sharp temperature gradient in the vicinity of the junction between the heated and unheated portion. When the heated side of the shield was at 1,500° F, the temperature of the unheated side was about 300° F. Despite these severe conditions, no damage or distortion of the shield was observed. The thermal expansion of this heat shield was accommodated mainly as indicated in figure 1; however, radial deflections of the supports provided some additional expansion capability.

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Wind-tunnel tests.- Flat specimens approximately 12 inches by 24 inches were used for the wind-tunnel tests of the heat shield (configuration A) shown in figure 2. Two specimens were tested, one with a corrugation pitch of 1.16 inches and the other with a pitch of 1.50 inches. A specimen mounted in the tunnel ready for testing is shown in figure 8.

A characteristic of the Langley 9- by 6-foot thermal structures tunnel is that severe random pressure fluctuations occur during the starting and shutdown periods. Although the specimens were vented, pressure differentials greater than 10 pounds per square inch were observed across test specimens. The turbulence that occurred during the shutdown period eventually destroyed both specimens; however, the specimens withstood the stabilized operating conditions of the tunnel without any apparent damage. Five tests were made on the two panels and are described in the following paragraph.

The specimen with a corrugation pitch of 1.16 inches was tested with the axes of the corrugations alined with the airstream and survived without incident. The same specimen was tested with the axes of the corrugations at an angle of 45° to the airstream. At tunnel shutdown, the specimen was destroyed. For this latter test a different method of venting was used which resulted in a more violent pressure differential across the panel than in the first test. In subsequent tests, the specimens were vented similar to the first test.

The panel with a corrugation pitch of 1.50 inches was tested with the axes of the corrugations alined with the airstream and received minor damage. During the tunnel start, a pressure wave buckled one corrugation crest inward, but the specimen survived the remainder of the test without further incident. After the test, the buckle was forced out and the corrugated surface snapped back to its original shape. The specimen was then tested with the axes of the corrugations at an angle of 45° to the airstream. Again a buckle appeared in the same place during the starting period but no further damage occurred. The buckle was again removed and the panel tested with the axes of the corrugations perpendicular to the airstream. Part of the panel was destroyed during the starting period and the remainder was destroyed during the shutdown period.

It should be emphasized that in all tests the specimens withstood the steady-state tunnel test conditions without flutter or any damage, and that the failures were due to large transient pressure differentials at tunnel startup or shutdown.

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Configuration B

Heating tests.- The shield design shown in figure 3 (configuration B), together with the underlying corrugated skin panel, was tested under radiant-heating conditions with maximum shield temperatures greater than 2,100° F and a temperature-rise rate of 20° F per second. The flat structural panel rested on four point supports, but it was not fastened or restrained in any way. A schematic diagram of the test setup is shown in figure 9. Several specimens with varying design details were tested and the results are shown in table I. The dimensions that were varied were support spacing and the corrugation depth. A shield with a corrugation depth of 0.070 inch performed satisfactorily, while shields with depths of 0.022 inch to 0.040 inch buckled between supports. It was found from specimen 1 that if the shield were not fastened at every corrugation trough along an edge attachment line, buckling occurred between fasteners. Specimen 2, originally identical to specimen 1, was modified by increasing the number of attachments along an edge to every corrugation trough. The type of buckling that occurred in specimen 1 was virtually eliminated. Figure 10 shows three heat shields after testing: one with inadequate corrugation depth, resulting in overall shield buckling, one with inadequate number of fasteners, causing buckling along the edge, and one that performed satisfactorily.

Because the shield is in close proximity to the structure, there is a substantial amount of heat transfer to the structure, especially in attachment areas. Specimens 1 to 4 had the attachment design indicated in the top sketch of figure 11. Note that in some areas only a thin layer of insulation separated shield and structure; the structural temperature in these regions was considerably greater than the average temperature. At screw locations there was undesirable metal-to-metal contact. In order to improve this situation, specimens 5 and 6 were fabricated with washers of boron nitride used as standoffs. (See bottom sketch in fig. 11.) The washers allowed a thicker, uniform insulation layer between shield and structure and considerably reduced metal-to-metal contact at the screw locations. The improvement in insulation efficiency is illustrated by the temperature curves shown in figure 11. Note the substantial temperature difference between shield and structure, especially in the early part of the test.

Wind-tunnel tests.- After the heating tests, wind-tunnel tests, similar to tests previously described, were conducted on specimens 2, 3, and 4 of design configuration B. However, a protective door shielded the specimen during starting and shutdown. Figure 12 is a photograph of a specimen in the tunnel and illustrates the operation of the protective door. At the start of a test the door is closed and completely covers the specimen. After stable tunnel conditions are established, the door is opened. Just prior to tunnel shutdown the door is again closed to shield the specimen as the shock wave passes through the test section. This door was inoperative for the shutdown for the test of specimen 2, but the only damage that occurred was a slight bowing of the structural panel.

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Each specimen was oriented so that the axes of the corrugations were parallel to the airstream with the lap splice facing away from the airstream. Two additional tests were made on specimen 4, one with the axes of the corrugations at right angles to the airstream and the other with the lap splice facing into the airstream. No flutter, vibration, or damage occurred to the heat shields in any of these tests. The corrugation depth of specimen 4 was such that performance was marginal in the heating tests, yet the corrugation was stiff enough to perform satisfactorily in the wind-tunnel tests.

Configuration C

The heat shield shown in figure 4 (configuration C) was tested as a flat panel under radiant-heating conditions only and in the same manner as previously shown in figure 9. As seen in figure 4, the passages in the underlying aluminum structural panel contained a cellulose sponge saturated with water which provided a passive water-wick cooling system. As long as a significant amount of water was in the passages, the panel temperature was never greater than a few degrees above the boiling point of water, even at lines midway between cooling passages.

The heat shield was heated at rates as high as 50° F per second up to test temperatures of 1,600° F, 1,800° F, and 2,000° F. The shield was held at these temperatures until the aluminum panel indicated a temperature rise above the boiling point of water. This period varied from 10 to 20 minutes. Inasmuch as the temperature of the aluminum panel was only a little over 200° F, a substantial temperature difference between shield and structure occurred over an extended period of time.

A temperature difference of about 100° F, which existed between the deeper underlying corrugation and the outer surface of the shield during the initial portion of the test, disappeared after test temperature was reached. Inspection during and after the test showed that little distortion or permanent damage was caused by this initial temperature difference. The slight amount of permanent distortion that was present along the edges after the test can be seen in figure 13.

CONCLUSIONS

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The results of the aerodynamic tests and radiant-heating tests made on the different heat-shield designs indicate that:

1. Thin-gage material (on the order of 0.01 inch) will perform satisfactorily when used in a properly designed heat shield.

2. A slightly corrugated outer surface in combination with a somewhat flexible supporting system can accommodate large temperature differences (approximately $2,000^\circ$ F) between heat shield and underlying primary structure. Certain values of corrugation depth and support spacing are necessary to produce satisfactory results.

3. The two designs that were tested in a Mach 3 wind tunnel withstood dynamic pressures of at least 3,000 pounds per square foot.

4. The general heat-shield-design concepts presented could be used in the design of refractory-metal heat shields capable of sustaining temperatures well above $2,000^\circ$ F.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., January 25, 1962.

TABLE I

EFFECT OF CORRUGATION DEPTH AND SUPPORT SPACING ON BEHAVIOR OF HEAT SHIELDS, CONFIGURATION B, SUBJECTED TO RADIANT HEATING

Specimen	Corrugation depth, in.	Support spacing, in.	Insulation	Remarks
1	0.070	3.50	Two sheets 0.040-inch-thick Fiberfrax plus Thermoflex	Inadequate tiedown of top sheet. Results indicate that along an edge, each corrugation should be held down by a fastener.
2	.070	3.50	Two sheets 0.040-inch-thick Fiberfrax plus Thermoflex	Addition of sheet-metal screws resulted in a panel which showed little deformation during or after heating.
3	.026	4.25	Two sheets 0.040-inch-thick Fiberfrax plus Thermoflex	Corrugations not deep enough. Heat shield buckled before developing enough force to actuate expansion mechanism.
4	.040	4.25	Two sheets 0.040-inch-thick Fiberfrax plus Thermoflex	Corrugations not deep enough. Heat shield buckled before developing enough force to actuate expansion mechanism.
5	.030	4.25	1/8-inch-sheet of Min-K2,000 plus ceramic washer	Improved insulating qualities over specimens 1 to 3. Inadequate corrugation depth resulted in buckling of heat shield.
6	.022	4.25	Four sheets 0.040-inch-thick Fiberfrax plus ceramic washer.	Superior in insulation effectiveness. Insufficient corrugation depth.

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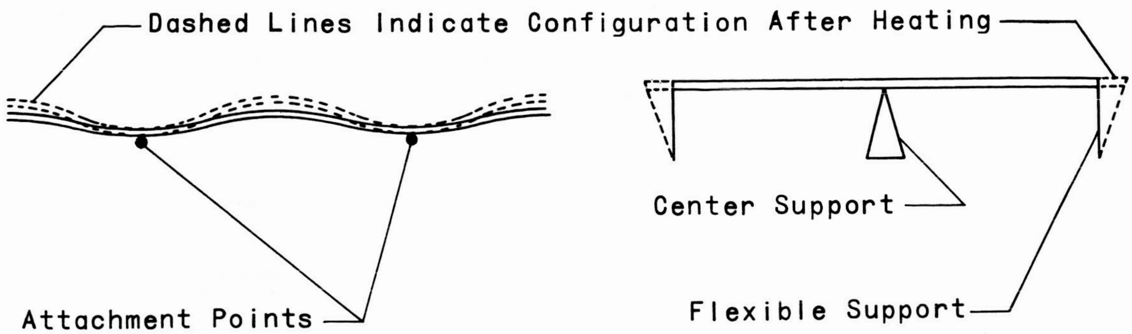


(a) Expansion perpendicular to corrugation axis.

(b) Expansion parallel to corrugation axis.

Figure 1.- Mechanisms accommodating thermal expansion for a corrugated sheet.

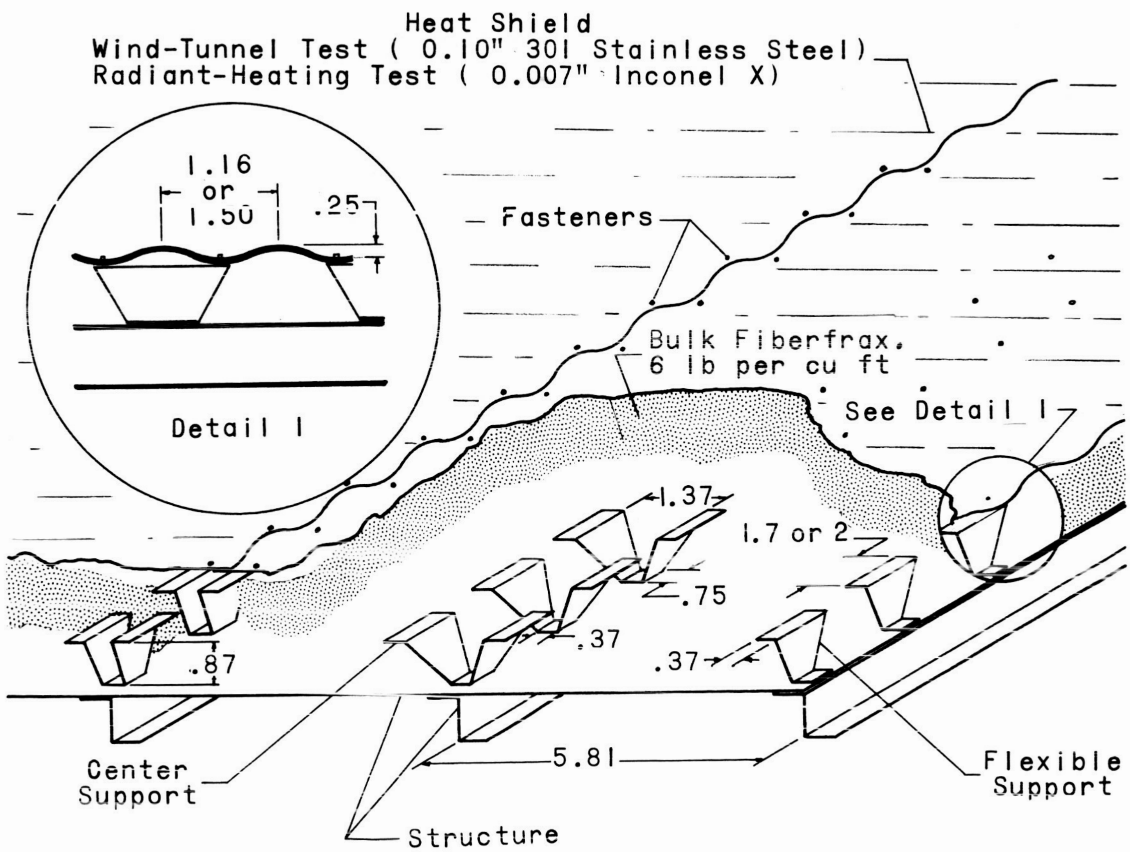
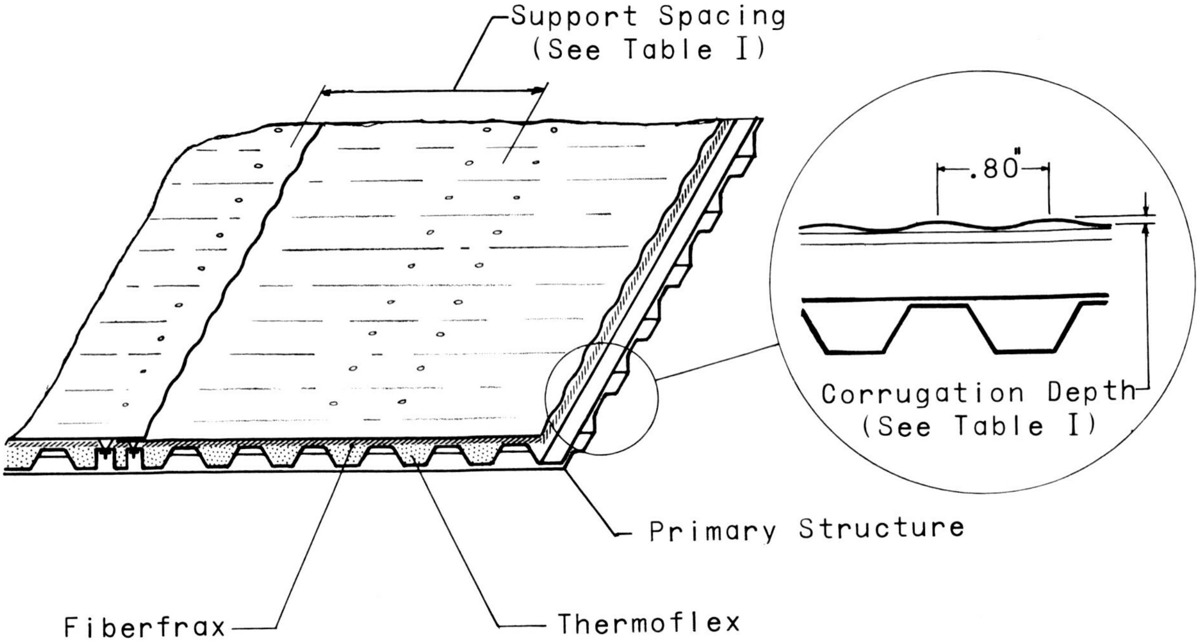
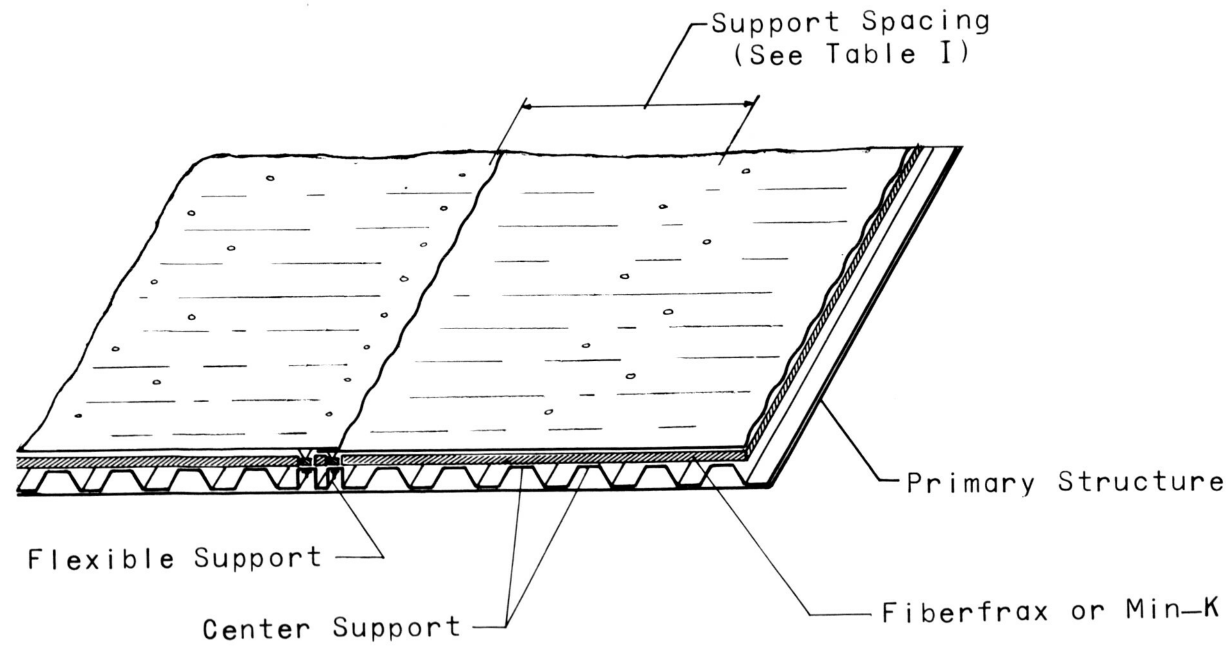


Figure 2.- Details of heat-shield design, configuration A. All dimensions are in inches unless otherwise noted.



(a) Specimens 1 to 4.



(b) Specimens 5 and 6.

Figure 3.- Details of heat-shield design, configuration B.

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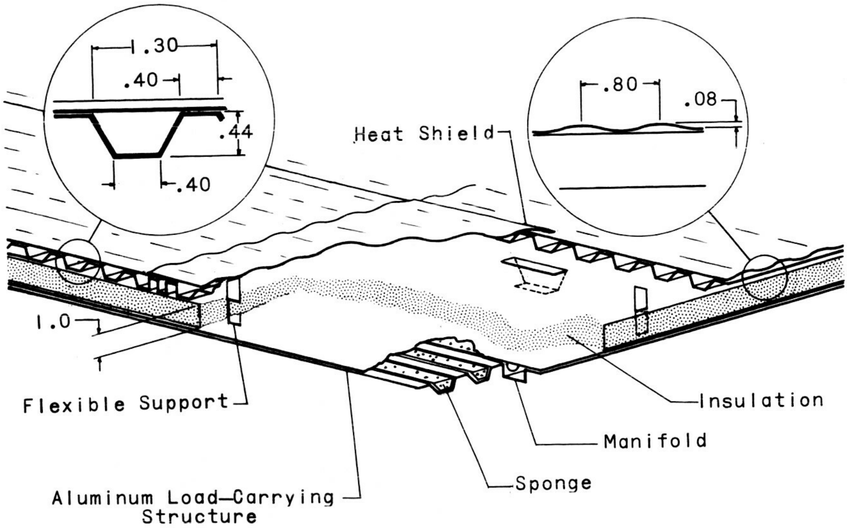

Figure 4.- Details of heat-shield design, configuration C. All dimensions are in inches.

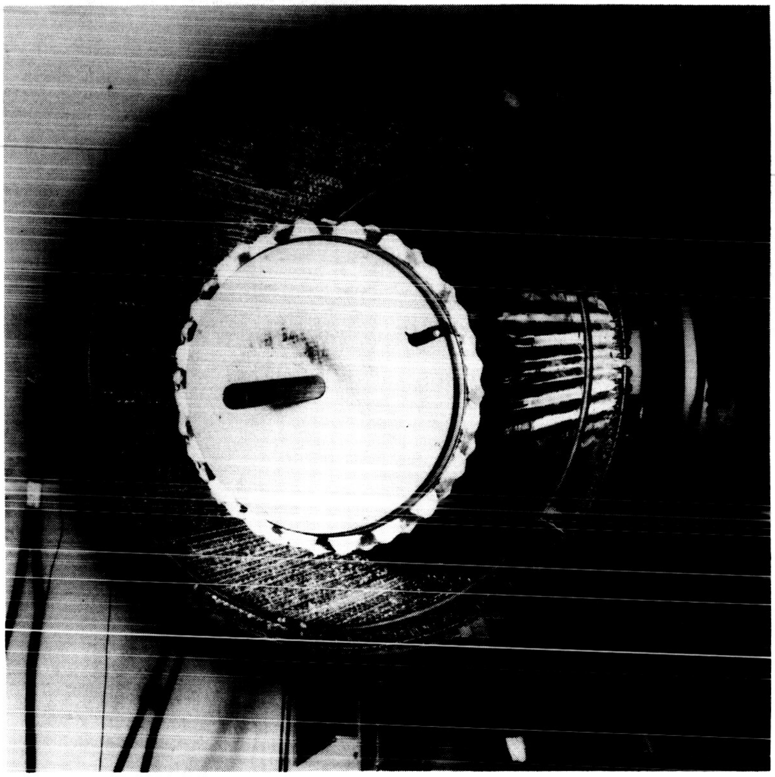

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Figure 5.- Cylindrical heat-shield specimen mounted in radiant heater.

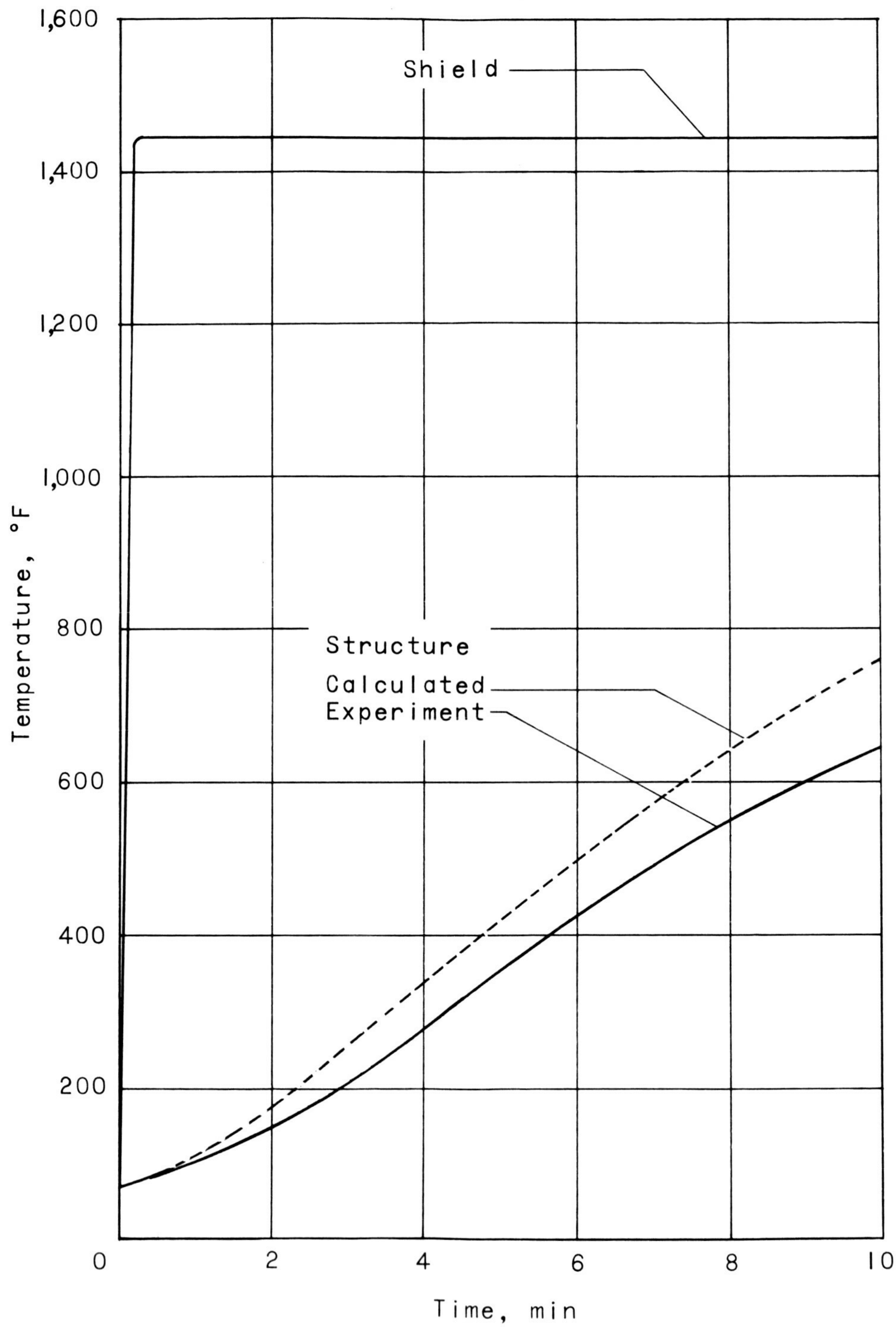

Figure 6.- Theoretical and measured temperatures for cylindrical heat shield and underlying structure.

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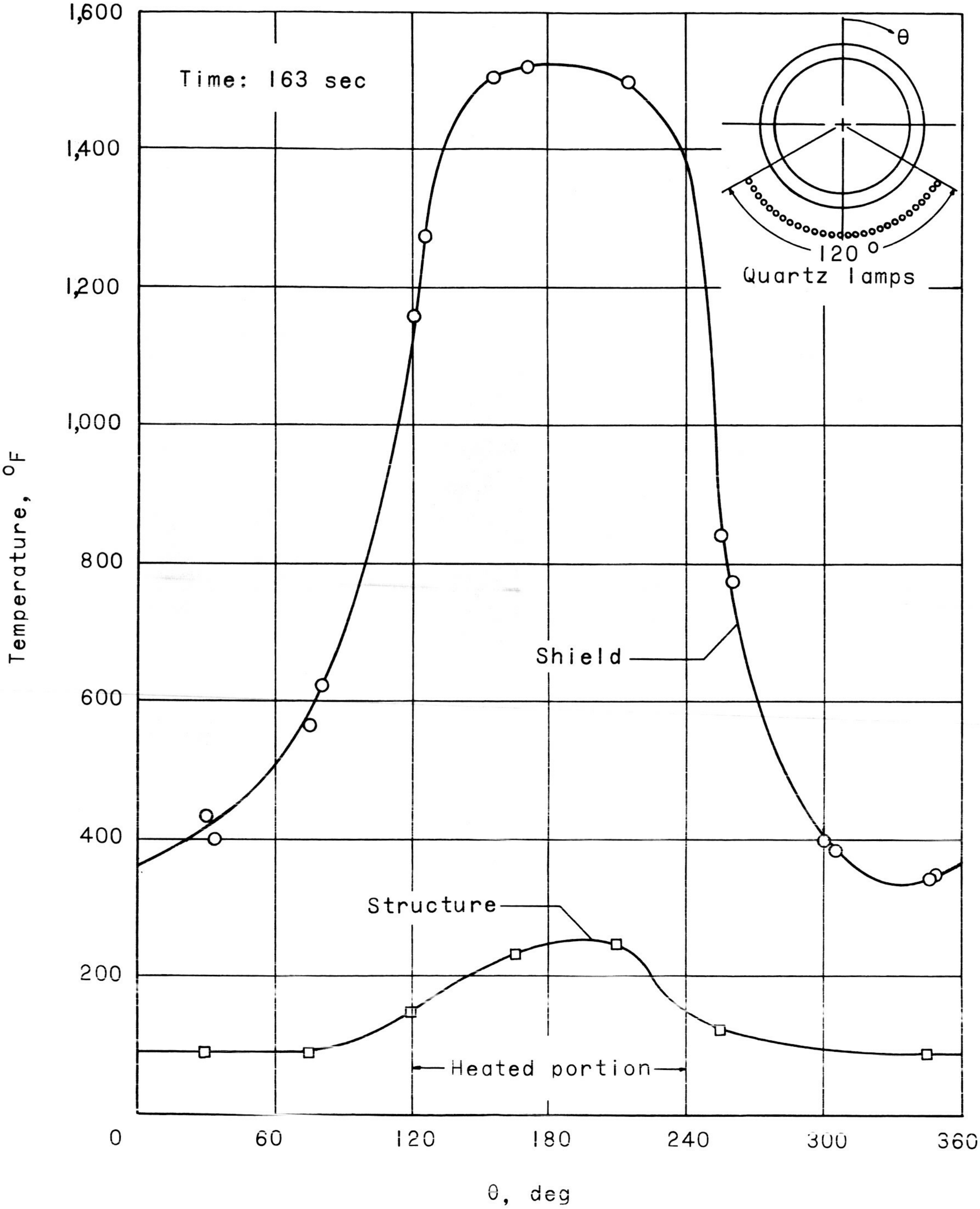

Figure 7.- Heat-shield and structural temperatures resulting from heating applied to one-third of specimen circumference.

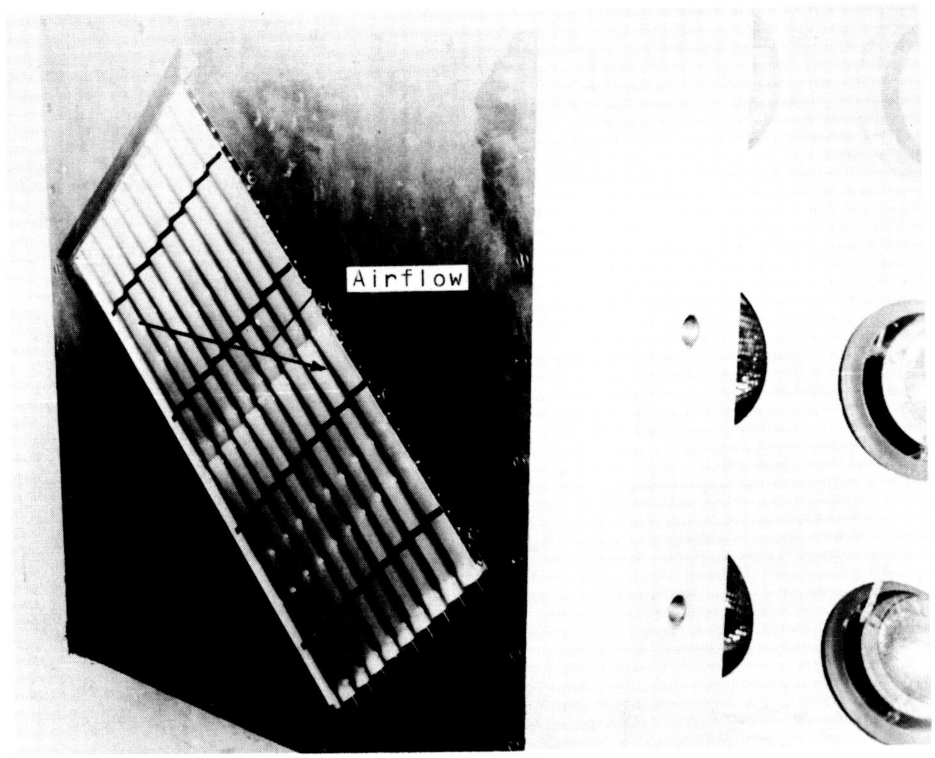

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Figure 8.- Corrugated heat shield mounted in panel holder in Langley 9- by 6-foot thermal structures tunnel.

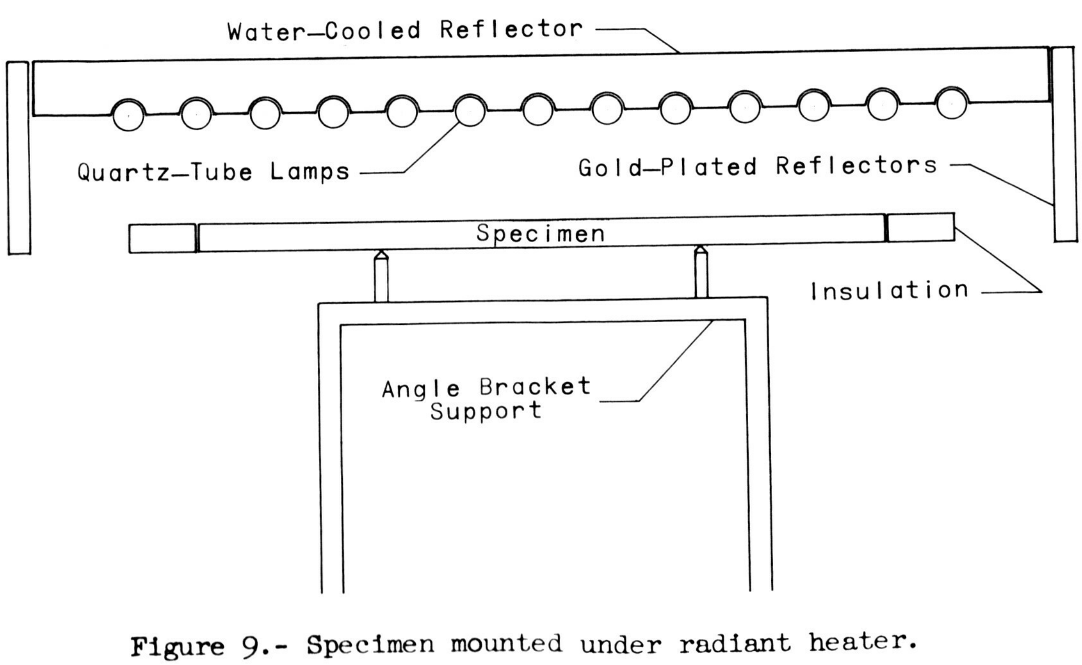
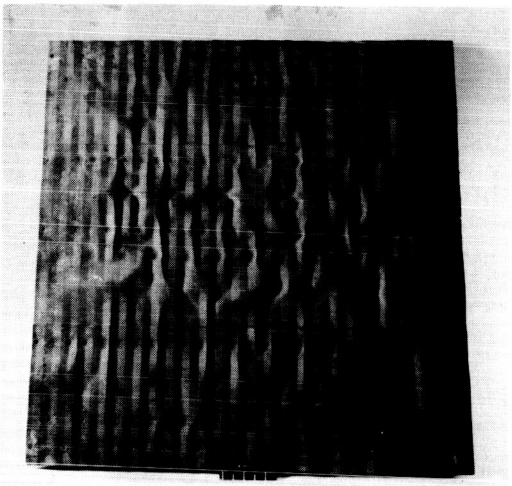
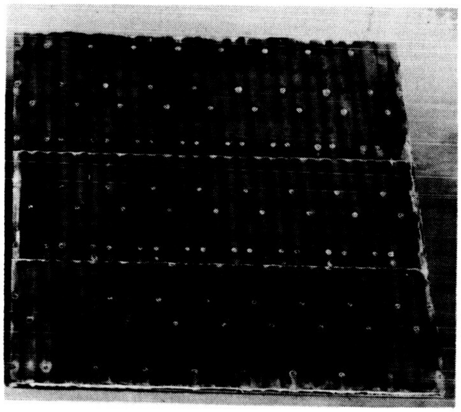


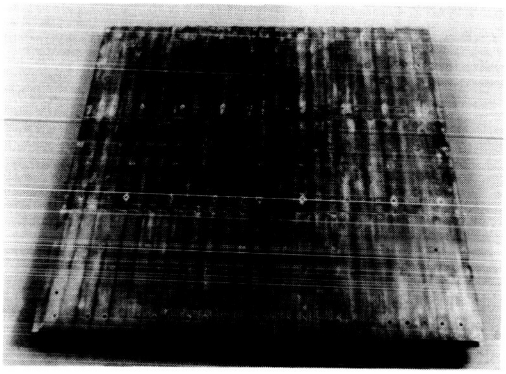
Figure 9.- Specimen mounted under radiant heater.



(a) Inadequate corrugation depth; overall shield buckling.



(b) Inadequate number of fasteners; buckling along edge.



(c) Satisfactory performance. L-62-23

Figure 10.- Three different heat-shield specimens after radiant-heating tests.

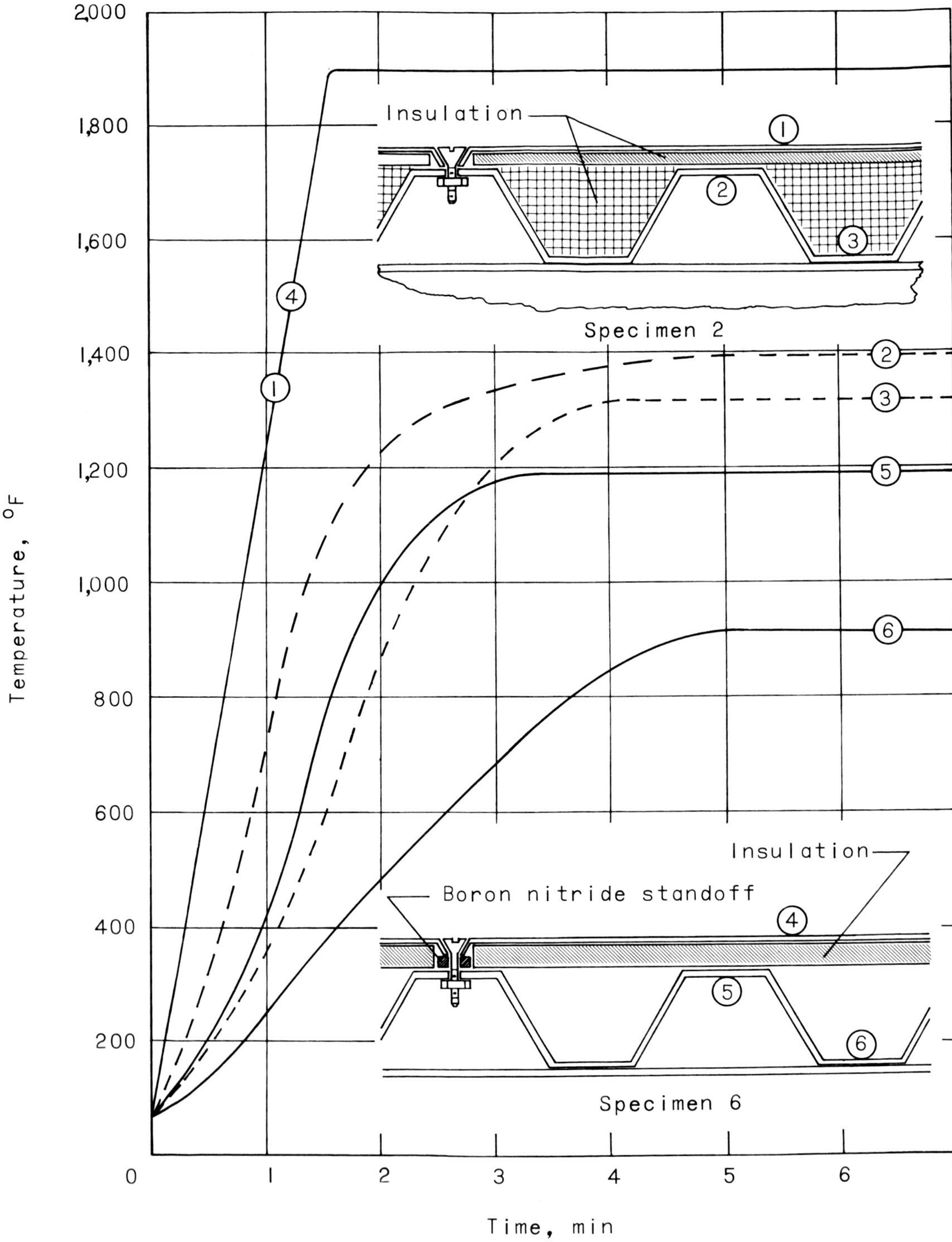


Figure 11.- Temperature response of heat-shield specimens 2 and 6 (configuration B). Circled numbers indicate thermocouple locations.

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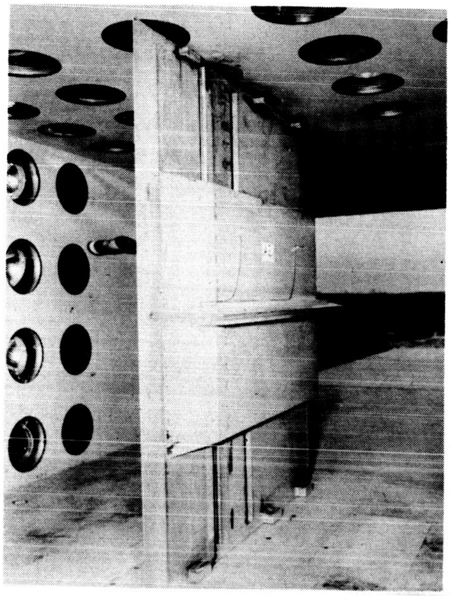
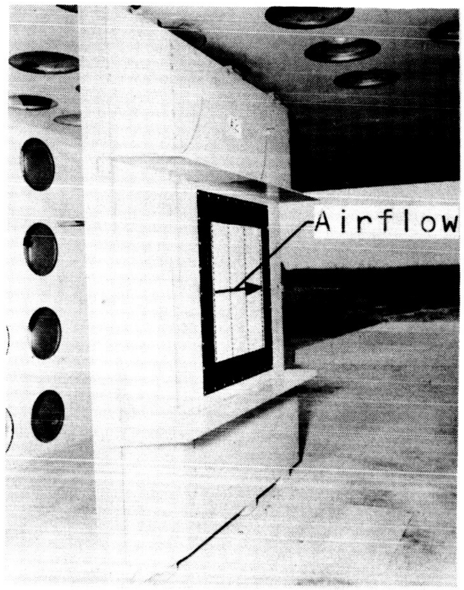


(a) Door closed.



(b) Door open. L-62-24

Figure 12.- Heat-shield specimen mounted in panel holder with protective door in Langley 9- by 6-foot thermal structures tunnel.

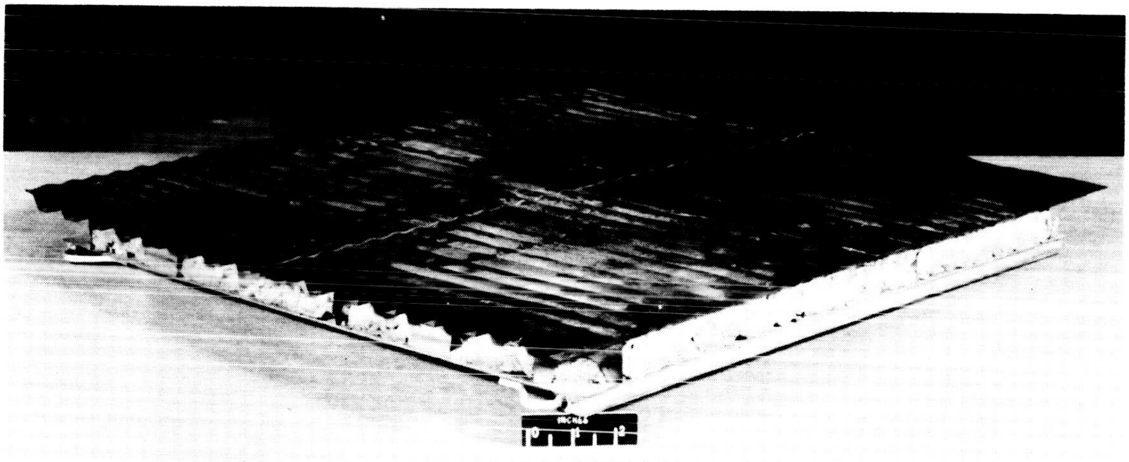


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Figure 13.- Two-ply corrugated heat shield mounted on water-cooled aluminum panel. Heat shield has been exposed to a temperature of 2,000° F.